Stress Analysis of Terminals From the Distribution of Screening Currents for the 40 T All-Superconducting Magnet Project

P. Xu, D.K Bond, I.R. Dixon, *Senior Member, IEEE*, and H. Bai

***Abstract*—Stresses created by screening currents in high field superconducting magnets constructed of rare-earth barium-copper-oxide (REBCO) tapes have been shown to be a major issue that has led to reduced performance of some REBCO coils. Some superconducting alloys suffer more than REBCO when it comes to the degradation due to stress. It is becoming more commonplace to include the effects of screening currents in the design of REBCO coils. A 2D T-A electromagnetics model coupled with a structural COMSOL finite element model have been implemented to analyze strain from screening currents in the design of the 40 T all-superconducting magnet and associated test coils at the National High Magnetic Field Laboratory. The T-A model considering transport current parallel to the plane was verified with the H-formulation. This model has been expanded to a 3-D structural model to investigate the strain in the REBCO terminals, which interface REBCO pancake-wound coils with the coil leads. The effects of non-uniformly distributed magnetic field from the coil are considered and coupled with the screening current in the terminal. The stress and strain of multi-tape terminals caused by the screening currents are investigated and discussed. The calculated axial strain is less than 0.3%, which is within the limit of the yield strain for REBCO coated conductors. The developed model can be used to simulation more complex geometry with different directions of transport current and background field.**

***Index Terms*—Electromagnetic modeling, finite element analysis, high temperature superconducting materials, screening current, superconducting magnet.**

I. Introduction

The advantages of high engineering critical current density, high strength, and high critical magnetic field of REBCO-based second generation high temperature superconductors (2G HTS) enable pushing the limit of high field magnets [1], [2], [3], [4], [5], [6]. However, screening currents generated by the penetration of the radial field of the magnet into the REBCO tape could be higher than the transport current, which leads to the screening current induced field (SCIF) and screening current induced strain [7], [8], [9]. In high field magnets constructed of REBCO tapes, the stresses generated by screening currents have shown to be a major issue that has led to the reduced performance of some REBCO coils [10]. Therefore, it is necessary to consider the effects of screening currents in the design of REBCO coils.

Finite element analysis (FEA) is commonly used to solve the Maxwell equations to model the screening currents by Multiphysics coupling of the electro-magnetic effect [11], [12]. The H-formulation is widely used by more than 45 research groups [13], [14], [15] to solve the Maxwell equations because it is easy to implant in the commercial software COMSOL [16]. However, it is computationally expensive as it considers the superconducting and air region together in the H-formulation, thus it becomes difficult to model large scale coils, e.g., 40 T superconducting magnet. H-φ formulation [17] has been proposed to speed up the computation because it considers the superconducting regime and air regime in the H-formation and φ formulation separately. A T-A formulation [18], [19] was developed to assume infinitely thin strip (1D) for the tape and considers the current vector T-formulation in the superconducting area and the magnetic vector A-formulation for the whole regime. This method has been extended and verified to consider multi-scale and homogeneous [20] simplification for modeling of large-scale coils in real time simulations. However, the above methods considered the transport current perpendicular to the simulated geometry, thus, the transport current and the generated screening current are only in one direction. For a long REBCO tape terminal, or current lead that provides the current to energize the coil, the transport current is parallel to the tape, which generates screening current in two directions: axial and circumferential, where the axial direction is perpendicular to the coil plane and the circumferential direction is along the tape winding. In addition, the background field along the terminal tape is not uniformly distributed. It is essential to develop a model that can analyze the screening currents in the two directions and the generated stresses.

II. Analysis Method

A. 2-D T-A Formulation

The governing equations for the general forms are:

$$J = \nabla \times T \quad (1)$$

$$B = \nabla \times A \quad (2)$$

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where J is the current density, T is the current vector, B is the magnetic flux density, and A is the magnetic vector. For a 2D geometry, (1) is written as:

$$J_x = \partial T/\partial y \quad (3)$$

$$J_y = \partial T/\partial x \quad (4)$$

The Maxwell-Faraday's law is expressed as

$$\nabla \times E = -\partial B/\partial t \quad (5)$$

where E is the electrical field, following the E-J power law

$$E = \rho_{HTS} J = E_c\, J/J_c\,(B)\, |J/J_c\,(B)|^{(n-1)} \quad (6)$$

where E_c is the critical electric field at 10^{-4} V m^{-1}, J_c is the critical current density and n is the superconducting n-value. Both J_c and n can depend on the magnetic field.

The Ampere's law is expressed as

$$\nabla \times \nabla \times A = \mu_0\, \mu_r J \quad (7)$$

where μ_0 and μ_r are the magnetic permeabilty and relative permeability of the free space, respectively.

The transport current is applied as a Dirichlet boundary condition in the T formulation as the following:

$$I = (T_1 - T_2)\, \delta \quad (8)$$

where δ is the width of the tape. Since the transport current is parallel to the plane, a continuous boundary function is applied at the top and bottom edges to constrain the current.

The current distribution obtained from the T-formulation is the input into A-formulation as external current. Therefore, (7) can be rewritten in the A-formulation model:

$$n \times (B_1 - B_2) = \mu_0\, \mu_r J \quad (9)$$

where n is the unit normal vector of the thin strip. B_1 and B_2 are the magnetic fields on the two sides of the REBCO strip.

B. 3-D Structural Mechanics Model

Once the electro-magnetic field is solved in the T-A formulation, the Lorentz force can be calculated by the magnetic flux density and the current desity as the following:

$$F_x = B_z J_y \quad (10)$$

$$F_y = -B_z J_x \quad (11)$$

$$F_z = B_y J_x - B_x J_y \quad (12)$$

where F_x, F_y, and F_z are the Lorentz body forces in the circumenferencial, radial, and axial directions of coil geometry in the cylindrical coordinates, respectively, with unit in N/m^3.

The calculated Lorentz force can be applied to the body load in the 3-D structural mechanic model. An example of the geometry of terminal is shown in Fig. 1. The transport current is supplied from the terminal tapes to the coil.

III. Model Verification

The model developed with the 2-D T-A formulation is verified with the H-formulation. A 2-D H-formulation is also developed because of the parallel transport current to the plane and the two-dimensional screening currents.

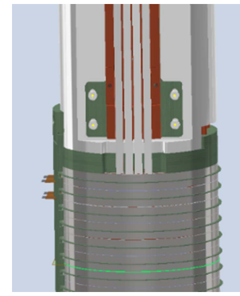


Fig. 1. Terminal with REBCO tapes. The 4 straight tapes in the axial direction are placed on top of the outer diameter of the coil. The copper block is placed behind the tapes for support.

A. 2-D H Formulation

The Faraday's law for H-formulation is the same as in the T-A formulation. The differences are that the H formulation solves the Maxwell equations with the magnetic vector H in the whole domain. The Ampere's law for H-formulation is expressed as

$$J = \nabla \times H \quad (13)$$

For a 2D geometry, (13) is written as:

$$J_x = \partial H/\partial y \quad (14)$$

$$J_y = \partial H/\partial x \quad (15)$$

Faraday's equation expressed in terms of magnetic field takes the form:

$$\partial\,(\mu_0 \mu_r\, \mathrm{H})/\partial t + \nabla \times (\rho \nabla \times H) = 0 \quad (16)$$

where ρ is a general electrical resistivity for both air and superconducting materials.

The background field is applied as a Dirichlet boundary condition. However, the transport current needs to be applied as a pointwise constraint P as the following

$$P = \int J_y \cdot t_h dx - I_{op} \quad (17)$$

where t_h is the thickness of the tape, I_{op} is the transport operating current applied to the terminal. It is important to note that the integration is conducted in every line segment in the geometry, where the long tape has been divided into several line segments in the axial direction. More refinement is necessary to accurately apply the transport current.

The REBCO tapes used for the terminal are 95 μm thick and 4 mm wide [8]. The critical current is calculated using Kim fit of tape M4-506 [8], the equation and fitting parameters are shown below:

$$I_c\,(B,) = \frac{I_{c0}}{\left(1 + \sqrt{k^2 B_z^2 + B_r^2}/B_0\right)^{\alpha}} \quad (18)$$

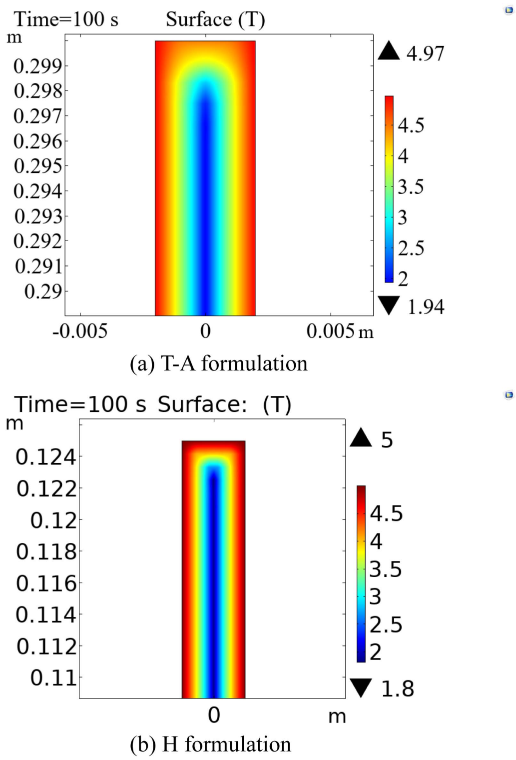


Fig. 2. Comparison of the magnetic flux density distribution at the top of the terminal tape between T-A (a) and H (b) formulation with an applied uniform background field of 5 T.

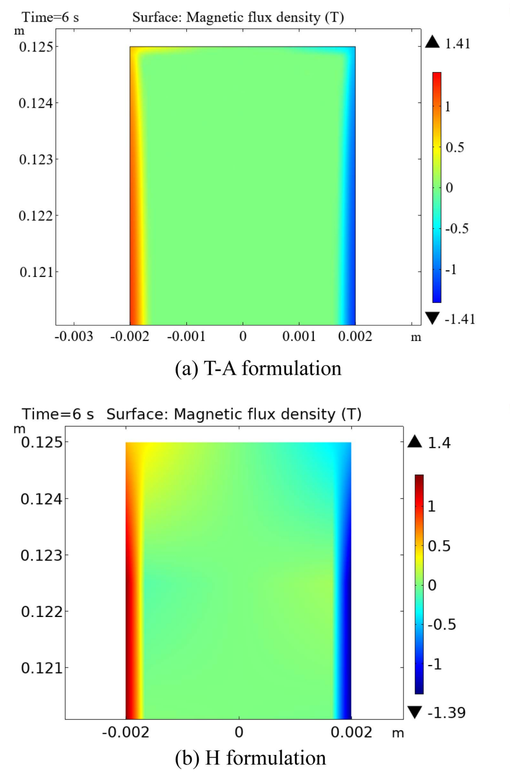


Fig. 3. Comparison of the magnetic flux density distribution at the top of the terminal tape between T-A (a) and H (b) formulation with the same transport current of 315 A.

where $I_{c0} = 2000\,A, k = 0.063, B_0 = 1.56\,T$, and $\alpha = 1.088$. The n value is assumes to be 25 [8] in the calculation. The magnet is operating the 4 K.

B. Comparison With Background Field

A uniform background field of 5 T is applied perpendicular to the plane of one terminal tape for both the 2-D T-A formulation and H-formulation model.

The Comparison of the magnetic flux density distribution at the top of the terminal tape between T-A and H formulation is shown in Fig. 2. The Comparison of the magnetic flux density distribution at the bottom of the terminal tape looks similar as the top and is not shown here. The magnitude and the distribution agreed well between the two methods.

C. Comparison With Transport Current

Another comparison is made by applying a transport current of 315 A parallel to the terminal tape for both the 2-D T-A formulation and the H formulation.

The comparison of the magnetic flux density distribution at the top of the terminal tape between T-A and H formulation by applying the transport current is shown in Fig. 3. The comparison at the bottom looks similar and it is not shown here. The magnitude and the distribution of the magnetic flux density agreed well between the two methods.

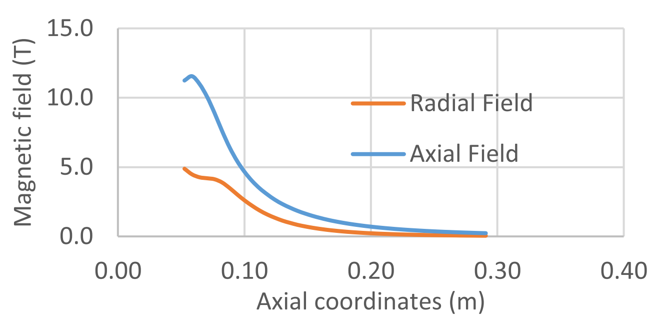


Fig. 4. The lengthwise radial and axial field applied to the terminal tapes.

IV. Results and Discussion

The developed 2-D T-A formulation model has been verified. It is then used to model the screening current and the induced stress for the terminal REBCO tapes. The lengthwise radial and axial field is applied to the tapes, shown in Fig. 4, the transport current of 78.5 A in each of the 4 REBCO tapes are applied. The current and field ramp are shown in Fig. 5.

A. Current Density Distribution

The current density distribution in the axial direction of the 4 terminal tapes is shown in Fig. 6. A non-uniform screening current density distribution is observed across the tape width of 4 mm because of the penetration of the radial field. There are also different distributions at the top and bottom of the tapes,

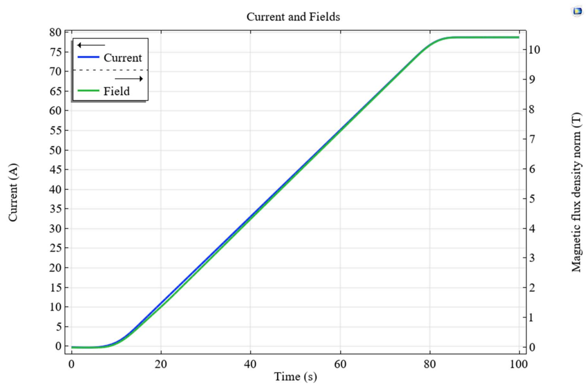


Fig. 5. Current and field ramp.

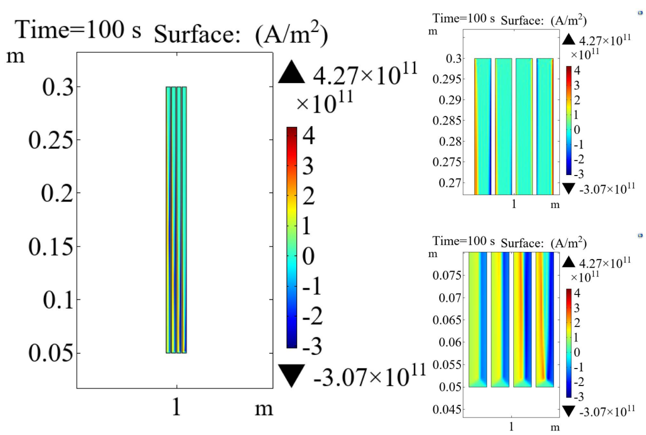
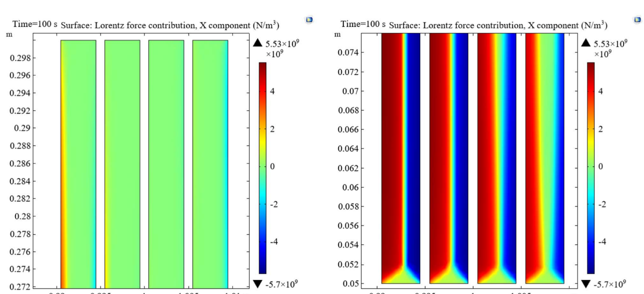


Fig. 6. Current density distribution at the axial direction, the right-hand side shows the images for the top and bottom current density distribution.



(a) Top (b) Bottom

Fig. 7. Lorentz force (N/m³) distribution at the circumferential direction, where (a) is at the top of the tapes, (b) is at the bottom of the long tapes.

which is due the non-uniform background field distribution in the axial and radial direction.

B. Lorentz Force

The Lorentz force density in the circumferential direction at the top and bottom of tapes are shown in Fig. 7. The positive and negative forces are due to the non-uniform distribution of the screening current density.

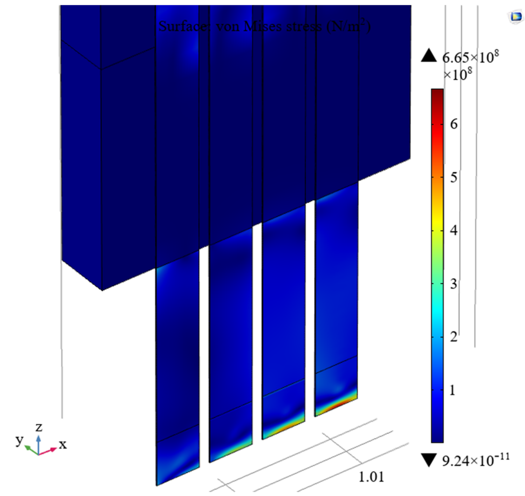
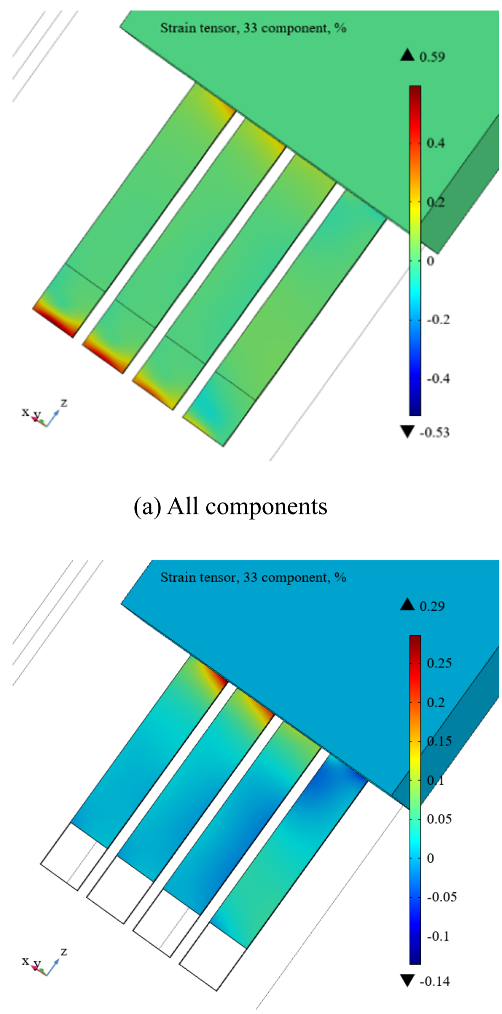


Fig. 8. von Mises stress distribution of the terminal tapes and the copper block at full field.



(a) All components

(b) Without 4 mm into the coil.

Fig. 9. Axial strain with all components (a) and without the 4 mm tape at the bottom inserted in the coil.

C. Stress Results

The Young's module used for the tape is 140 GPa [8] by considering the material properties of Cu, Hastelloy, and buffer layer. The von Mises stress distribution at full field is shown in Fig. 8. The maximum stress is about 665 MPa at the bottom edge of the tapes.

The axial strain of REBCO terminal tapes and the copper block is shown in Fig. 9, for (a) with all components and (b) without the tapes inserted into the coil. The terminal tapes are placed at the outer diameter of the disk, where the disk was reinforced by the over band stainless steel. The maximum axial strain is 0.59% at the bottom edge of the tapes. However, this part is constraint in the coil because the disk is built up with 4 mm width tapes and the terminal tapes are inserted into the coil. Fig. 9(b) shows the axial strain without the 4 mm tapes inserted into the coil (where it is constrained), the maximum strain is only 0.29%, where it appears at the interface between tapes and copper block.

V. Conclusion

A 2-D model with a T-A formulation considering the transport current parallel to the simulation plane with two directions of screening currents is developed and compared with the developed 2-D H-formulation. The model was verified and applied to simulate the screening current of the REBCO terminal tapes. The time dependent 2-D T-A electro-magnetic model is then coupled with the 3-D structural mechanics model to calculate the stress and strain in the terminal tapes. The calculated axial strain is less than 0.3%, which is within the limit of the yield strain for REBCO coated conductors. The developed model can be used to simulation more complex geometry with different directions of transport current and background field.

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